Measurement of turbulent thermal convection in liquid metal under uniform magnetic field

Takatoshi Yanagisawa[1*], Yasuko Yamagishi[1], Aataru Sakuraba[2], Yuji Tasaka[3], Kanako Yano[3], Yasushi Takeda[3], and Yozo Hamano[1]
[1] Institute for Research on Earth Evolution (IFREE), Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 2-15 Natsushima-cho, Yokosuka, Kanagawa 237-0061, Japan (*Corresponding author, e-mail: yanagi@jamstec.go.jp).
[2] Department of Earth & Planetary Sciences, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[3] Division of Energy & Environmental Systems, Hokkaido University, Kita-13, Nishi-8, Kita-ku, Sapporo 060-8628, Japan

UVP is used to visualize the flow of liquid gallium for Rayleigh-Benard convection. Measuring the horizontal component of the flow velocity for several lines, organized roll-like structure with many fluctuations is observed at Rayleigh number 10^4~10^6, and the roll shows clear periodic oscillatory behavior. The typical period of the oscillation is comparable to the circulation time of the mean flow. Our numerical simulation with the same setting and material properties confirms these features. When the uniform magnetic field is imposed on this convecting system, drastic changes of the flow are observed depending on the direction and intensity of the magnetic field. Horizontal magnetic field enhances the two-dimensionality of the roll-like structure, and vertical magnetic field reduces the velocity of the mean flow.

Keywords: Liquid metal, thermal convection, magnetic field, turbulence, velocity profile

1 INTRODUCTION

Thermal convection under the vertical temperature gradient is described by two non-dimensional parameters, Rayleigh number (*Ra*) and Prandtl number (*Pr*). The onset of the convective motion is controlled by critical *Ra* and independent of *Pr*, but after the convection occurs, the behavior of the system is strongly dependent on *Pr* [1]. It easily becomes turbulent for lower *Pr*. Molten metals are used for the study of low *Pr* region. Molten metals, however, are opaque fluids, so any optical methods for the flow measurement cannot be applied. Some works have been done by tracing the particle at the surface of mercury, and some have utilized the temperature dependence of sound velocity in liquid gallium and reconstructed roll pattern [2]. These works have been performed near the critical *Ra* where steady rolls exits. At higher *Ra* with extremely turbulent flow region (*Ra*~10^{10}), temperature is measured at some points in the convective cell, and the statistical features are discussed in the view of turbulence and heat transport in many studies [3], but direct measurement of convection pattern has been strongly desirable. The Ultrasonic Velocity Profiler (UVP) method [4] is a powerful tool to measure the flow occurring in the liquid metal. By using the UVP, *Mashiko et al*. succeeded in the direct measurement of convective velocity at high *Ra* region and found out a kind of large-scale flow existing in the cell [5], but their apparatus is a large tall cylinder in which only one main circulation occurs. The organization process to large-scale flow is not understood, so it is necessary to focus on the moderate *Ra* region.

On the other hand, liquid metals have large electric conductivity and the magnetic field affects the behavior of the flow. It is also important to study Rayleigh-Benard convection under various types of magnetic field. There are many experimental studies on this topic from critical to moderate *Ra* [6-8], but most of them are based on the measurement of temperature. Simultaneous measurement of velocity profile is also desirable to clearly grasp the characteristics of the flow.

Our aim of this study is to achieve a direct velocity measurement for Rayleigh-Benard convection in liquid metal and to look at the characteristic pattern at moderate *Ra* (10^4~10^6), whether there exits any mean flow with large-scale structure or not, and furthermore, in which way the external uniform magnetic field deform the structure and nature of the turbulence of the flow. The container for our experiment is horizontally long one to realize the intrinsic convection pattern.

2 APPARATUS AND METHOD

We use UVP to measure the fine-scale velocity field of the flow occurring in the liquid metal. Liquid gallium is used as the working fluid in our experiment. The container for convection is made of glass whose thickness is 10 mm. We choose Pyrex-glass because of its affinity to gallium and its impedance. Top and bottom plates are made of copper to keep the temperature constant by circulating water. The horizontal scale of the container is 200 mm, the other horizontal length is 50 mm, and height is 50 mm. The transducer for ultrasonic measurement is fixed on a sidewall, so the length of the measurement line is 200 mm. The horizontal component of the flow velocity at each line is measured in this system (Figure 1). The system we used for the measurement is UVP-Duo (Met-Flow inc.), and the basic frequency of the transducer is 4 MHz.

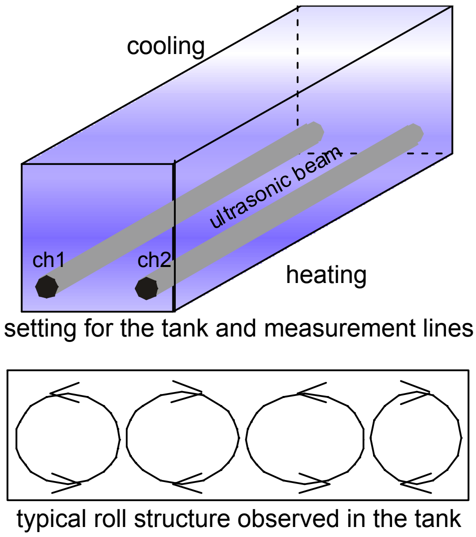

Figure 1: Schematic of the container and measurement lines by UVP (top). Liquid gallium is filled in the container. The typical convective flow pattern by vertical temperature difference has the roll like structure (bottom).

Powder of ZrB_2 is used as tracer particles because it has neutral buoyancy in liquid gallium. The typical diameter of the particles is 50 micrometer. To reduce the surface tension and to promote dispersion of the particles into liquid gallium, once we heated up the gallium up to 700 K. Gallium is easily oxidizable, so we handle it in argon gas. The melting temperature of gallium is 29.8 ºC, so the upper plate cooling temperature is fixed at 32.0 ºC, and lower plate heating temperature is raised up to 70.0 ºC. In the calculation of *Ra*, we used the material properties of gallium same as [9]. *Pr* of gallium around this temperature is 0.03. There is a small density difference between the tracer particles and liquid gallium; hence, the particles are gradually sinking even in convecting gallium. Then the reflection signals become weak, so we cannot continue UVP measurements for more than couple of hours.

Helmholtz coil system is used to impose uniform magnetic field on the container. We can set horizontal or vertical magnetic field, whose intensity is up to 20 mT. The diameter of the coil is 700 mm, and uniformity of the magnetic field is assured around the container. The maximum Hartmann number realized in this system is about 30. Three component of the magnetic field is monitored outside of the container by a magnetometer. Temperature is measured at some points inside of the liquid gallium by small-sized thermistors.

3 RESULT

3.1 Thermal convection without magnetic field

First, we report the result of simple Rayleigh-Benard convection, without magnetic field. We set the *Ra* one to three orders above the critical value, because the flow velocity is too small to be measured by UVP near the critical. Measuring the horizontal velocity at several sites in the container, many fluctuations are observed, that reflect turbulent behaviors of the flow. When we see the long-term tendency, we can reconstruct two-dimensional roll-like pattern (Figure 2). This roll-like pattern is supposed to be a kind of mean-flow which is the organized structure in the turbulence, and the small fluctuations may show the behavior of small vortices. The roll-like pattern shows clearly regular periodic behavior. This means that the roll structure gets longer and shorter sideways, and the axis of the rolls is swinging periodically. We found out that its period is comparable to the circulation time of the mean-flow, and gets shorter with the increases of *Ra*.

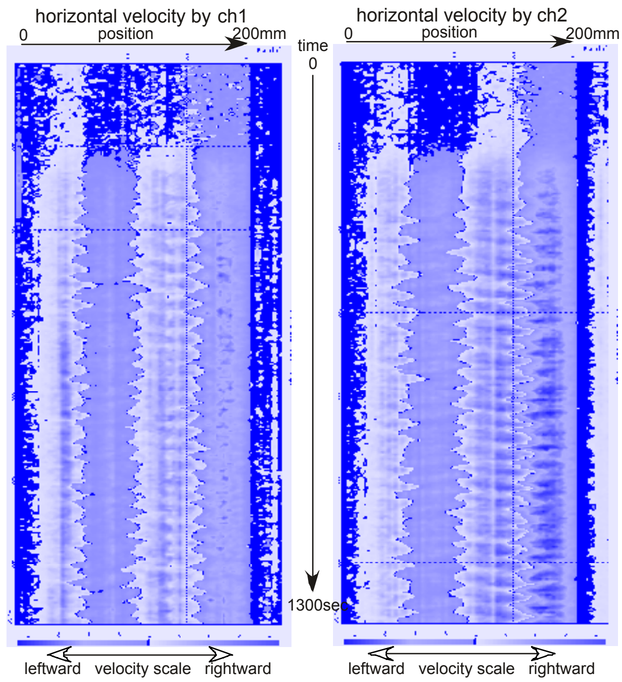

Figure 2: An example of the time series of the horizontal flow velocity. The measurement lines ch1 and ch2 are shown in Figure 1. Horizontal axis is the position, and vertical axis is the time. The magnitude of the velocity is displayed in grayscale. The top is the onset of convection, and four rolls are developed. The result clearly shows the periodic oscillations of the convective roll structure. *Ra*=1×10^5 for this case.

3.2 Numerical simulation for the same setting

We made up a code for numerical simulation of thermal convection to compare and evaluate our results obtained by laboratory experiments. The numerical simulation is for three dimensional rectangular box, with no-slip boundary conditions at all boundaries, fixed temperature at the top and bottom, and insulating at side walls. The material properties of the working fluid are those of liquid gallium. We used enough grid points to resolve the small-scale behavior without any assumption for the turbulence. Our numerical result reproduced oscillatory convection patterns as observed in the experiments (Figure 3). Some statistical values, such as the relation of the circulation time and oscillation period, *Ra* dependence of the mean velocity, are good agreement in both laboratory and numerical studies. This confirms that our laboratory experiment and numerical simulation are reliable ones.

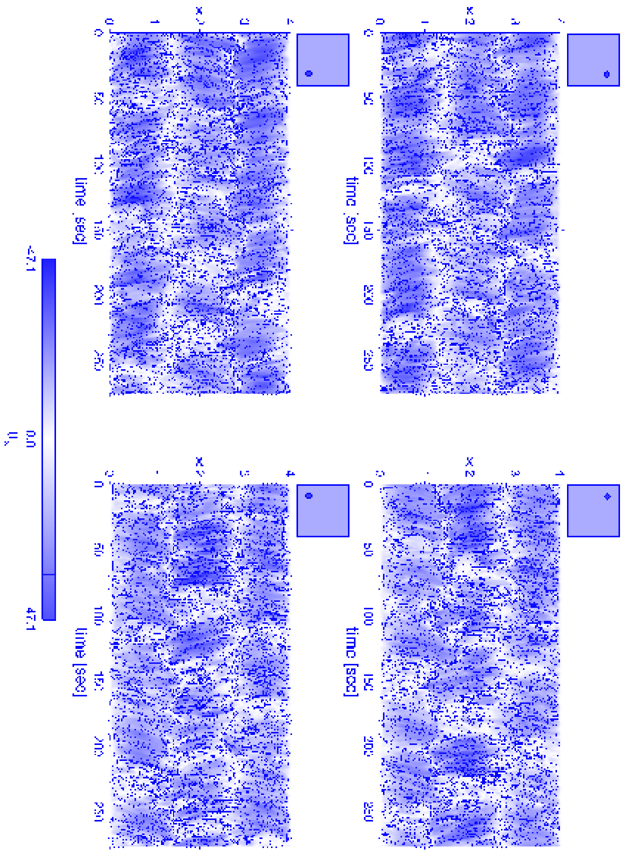

Figure 3: An example of the numerical simulation for the same setting as our laboratory experiment. Time series of the horizontal flow velocity is shown in the same way as UVP measurement. The features observed in Figure 2 (roll-like structure with small fluctuations, periodic oscillations of the rolls) are reproduced well. *Ra*=1x10^5, *Pr*=0.03.

3.2 Thermal convection under horizontal magnetic field

We measured the horizontal flow velocity in liquid metal with stepwise increase of the external magnetic field. We observed obvious change of the flow characteristics depending on the direction and intensity of the magnetic field.

Figure 4 shows the simultaneous measurement of velocity and temperature under horizontal magnetic field. The direction of the applied magnetic field is parallel to the mean roll axis of this convecting system, and its intensity is increased step by step. The basic flow structure, that is, the number of the rolls and its flow direction is not changed, but the fluctuating components of the flow are reduced remarkably and the mean velocity of the roll-like flow pattern is increased. The reduction rate of the fluctuation depends on the intensity of the applying magnetic field.

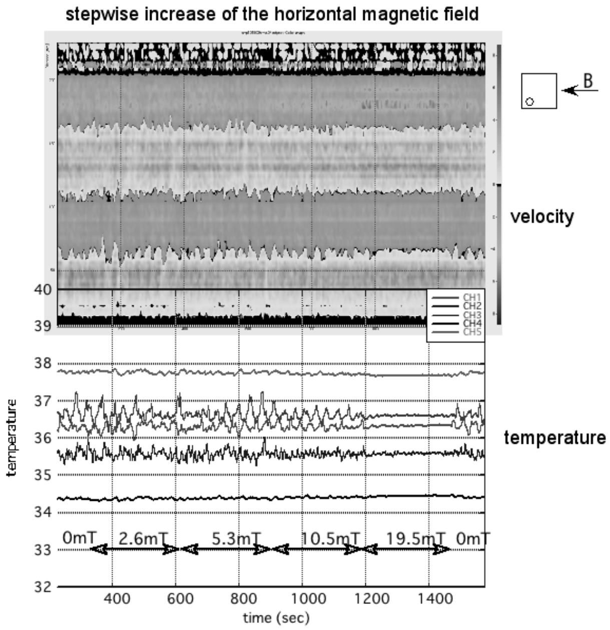

Figure 4: The behavior of the flow with stepwise increase of the horizontal magnetic field. *Ra*=1x10^5. Simultaneous measurement of horizontal velocity (top) and temperature (bottom) is displayed. Horizontal axis is the common time. In the bottom graph, three lines with large fluctuation are the signal from the thermistors inside of the liquid gallium. 0 mT, 2.6 mT, 5.3 mT, 10.5 mT, 19.5 mT, and again 0 mT, is the intensity of the imposed horizontal magnetic field. The reduction of fluctuating component is observed for both velocity and temperature from 5.3 mT, and the flow is almost steady for 19.5 mT.

3.3 Thermal convection under vertical magnetic field

Figure 5 is the result for the stepwise increase of vertical magnetic field. The basic flow pattern for 0 mT consists of four fluctuating rolls as in Figure 4, but the behavior with the increase of the magnetic field shows obvious difference. The typical flow velocity decreases with the increase of the magnetic intensity. At the same time, the typical period of the roll's fluctuation gets longer gradually. And little reduction of the fluctuation is observed except for 19.5 mT. The drastic reduction of random fluctuation is observed for this intensity, but periodic oscillation is survived.

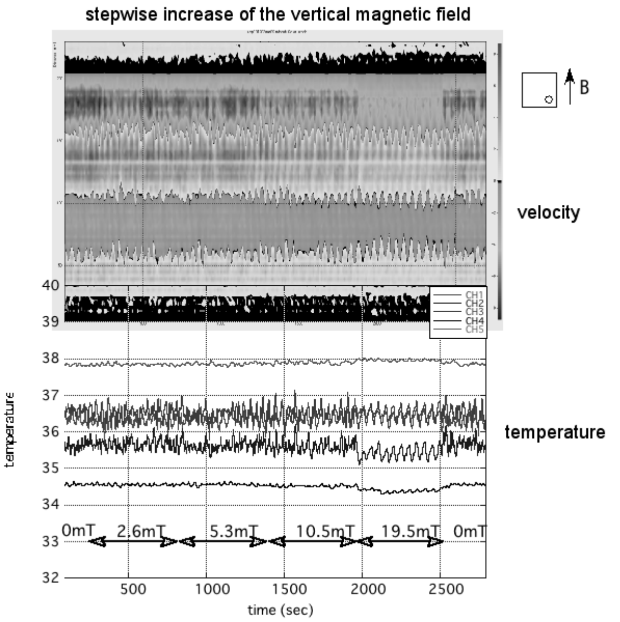

Figure 5: The behavior of the flow with stepwise increase of the vertical magnetic field. *Ra*=1x10^5. 0 mT, 2.6 mT, 5.3 mT, 10.5 mT, 19.5 mT, and again 0 mT, is the intensity of the imposed vertrical magnetic field. Typical flow velocity is decreasing with the increase of magnetic field, though it is not clear in this grayscale. Note that the total time in this series is longer than in Figure 4.

4 DISCUSSION

We succeeded in the measurement of velocity profile for the Rayleigh-Benard convection at low *Pr* with moderate *Ra*. Measuring the horizontal velocity at several sites of the container with the UVP, we can reconstruct two-dimensional roll-like pattern coexisting with small fluctuations. This roll-like pattern is supposed to be a kind of mean-flow, that is the organized structure in the turbulence, and the small fluctuations may show the behavior of small vortex. The periodic behavior of the roll-like structure is very important; it might show the interaction between the small vortex and the mean-flow. The velocity of the mean-flow becomes higher with the increase of *Ra*. At the same time, temporal fluctuation of the mean-flow field becomes faster. In the range of *Ra* 10^4~10^6, the UVP measurement shows that the typical velocity of the mean-flow *U* is proportional to $Ra^{1/2}$. The dependence of the typical period of the roll oscillation is $Ra^{-1/2}$, which suggests close relation between the mean-flow and the oscillation.

When we apply horizontal magnetic field along the roll axis of this convecting system, the fluctuating components are reduced and two-dimensionality of the roll structure is enhanced. The reduction rate of the fluctuation depends on the intensity of the applying magnetic field. We think that the criterion for the reduction is described by the comparison of two time scales, Joule dissipation time (t_{JD}) and circulation time (t_U). If $t_{JD} < t_U$, then strong reduction of the fluctuation may occur. This can explain the *Ra* dependence of our result that stronger magnetic field is necessary to stop the fluctuation of the roll for higher *Ra* (for larger *U*).

When we apply vertical magnetic field, the flow velocity and frequency of the periodic behavior reduces as the apparent *Ra* of the system becomes smaller. This is easily understandable because the critical *Ra* increases with the intensity of vertical magnetic field, then effective *Ra* for the fluid decreases.

5 CONCLUSIONS

Rayleigh-Benard convection with liquid metal is characterized by the organized roll-like structure and its fluctuation. This feature is confirmed both by UVP measurements and numerical simulations.

Horizontal magnetic field along the mean roll axis enhances the two-dimensionality of the flow structure, and decrease the fluctuation.

Vertical magnetic field reduces the effective *Ra* of the convective system.

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